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Hole levels in Ge self-assembled quantum dots probed with room temperature capacitance spectroscopy

*A. I. Yakimov, A. V. Dvurechenskii, V. A. Markov,
A. I. Nikiforov and O. P. Pchelyakov*

Institute of Semiconductor Physics, 630090 Novosibirsk, Russia

Abstract. Pyramidal Ge islands with the areal density $4 \times 10^{11} \text{ cm}^{-2}$ and the typical base length 12 nm have been grown on p-type Si (100) substrates at 300°C by molecular beam epitaxy. Capacitance spectroscopy was used to determine the allowed energy levels for holes in these quantum dots. At room temperature we observed the capacitance peaks with two types of spacings as a function of the gate voltage. The oscillations with largest period are attributed to the discrete quantum level structure while the peak splitting is a result of charging of dots by individual holes. The Coulomb charging energy is found to decrease with increasing of excited level number.

Self-assembled semiconductor islands created by epitaxial growth of lattice mismatched systems in the Stranski-Krastanow growth mode have the narrow size distribution and the extremely small lateral dimensions. Therefore, this approach is expected to produce quantum dots with superior electronic performance at room temperature. The most widely studied system so far is (InGa)As/GaAs (see [1] and references therein). The formation of three-dimensional islands after deposition of typically a few monolayers (ML) has also been observed for Ge/Si systems [2, 3]. The existence of single-electron phenomena in Ge/Si double-barrier heterostructures containing quantum dots at liquid helium temperature has been demonstrated by conductance spectroscopy [4]. A powerful technique for probing low-dimensional structures is the measurement of capacitance [5-7]. In this paper we report the results of capacitance measurements on Ge self-assembled quantum dots grown by molecular beam epitaxy on Si (100). Our experiments reveal the structure in the capacitance at room temperature related to the presence of quantum hole levels in Ge islands as well as the Coulomb charging effects.

The layer sequence of the sample studied is as follows: a p^+ -doped (10^{19} cm^{-3}) Si(001) substrate; a 200 Å $\text{Si}_{0.75}\text{Ge}_{0.25}$ bottom electrode; a 80 Å undoped Si tunnel barrier; self-assembled Ge islands formed from a coverage of 10 ML at growth temperature 300°C and growth rate 0.35 Å/s; a 600 Å Si blocking barrier; and a circular Al Schottky gate (400 μm diam). The Ge clusters have a pyramid shape [2] with the typical base length of 120 Å, their areal density is $4 \times 10^{11} \text{ cm}^{-2}$ [4]. The capacitance was measured with a lock-in amplifier at 300 K. The data were taken only at voltages where the signal was purely capacitive. We worked at frequencies below 100 kHz, where there was no frequency dependence. The ac bias used was 5 mV rms. The measurements were reproducible and did not show any hysteresis with changes of the gate voltage.

In capacitance-voltage curve we observe four well-resolved steps with period 0.23–0.33 V (Fig. 1).

These steps directly reflect the change in the density of hole states as the Fermi energy passes through successive discrete levels (labeled as E_0 , E_1 , E_2 , and E_3 , respectively)

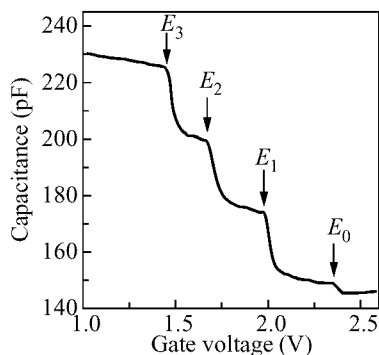


Fig 1. Capacitance-voltage characteristic.

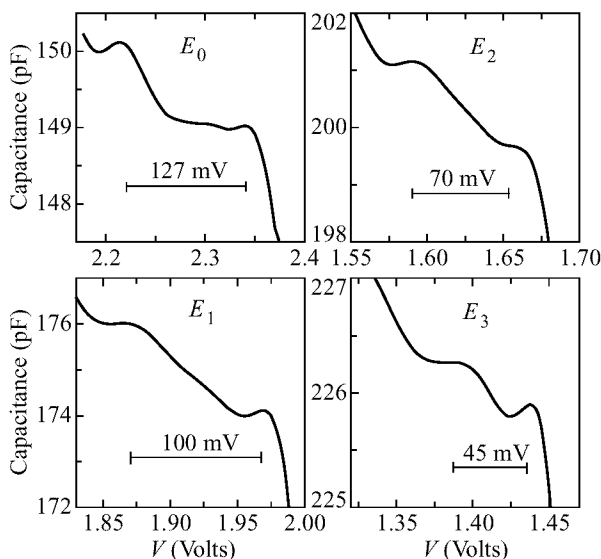


Fig 2. Expanded view of the four capacitance shoulders.

in quantum dots. An expanded view shows that each capacitance shoulder consists of two peaks (Fig. 2).

The gap between the split peaks gradually decreases from 127 mV for the ground hole state E_0 to 45 mV for the third excited state E_3 . We suggest Coulomb charging may be the origin of the peak splitting. Usually the single-electron charging energy is calculated as e^2/C , where C is the self-capacitance of the dot, independent on the quantum level structure. This approach is valid only for a system which contains a large number of electrons. In the opposite case, one must take into consideration the real shape of the particle wave functions in the dot. The electronic structure in pyramidal quantum dots was calculated by Grundmann et al [8]. They found that the hole ground state is squeezed at the bottom of the dot, the wave functions of the excited states are located along the opposite sides of the pyramide base or in the pyramide corners. The strength of the Coulomb interaction is determined by the wave-function overlap of the

holes in all occupied states. With increasing energy the overlap is reduced and hence the Coulomb energy gets smaller.

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